EMC Effect, Short-Range Correlations in Nuclei and Neutron Stars

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Abstract

The recent $x > 1$ (e,e') and correlation experiments at momentum transfer $Q^2 \geq 2\,\mathrm{GeV}^2$ confirm presence of short-range correlations (SRC) in nuclei mostly build of nucleons. Recently we evaluated in a model independent way the dominant photon contribution to the nuclear structure. Taking into account this effect and using definition of x consistent with the exact kinematics of eA scattering (with exact sum rules) results in the significant reduction of $R_A(x,Q^2) = F_{2A}(x,Q^2)/F_{2N}(x,Q^2)$ ratio which explains $\sim 50\%$ of the EMC effect for $x \leq 0.55$ where Fermi motion effects are small. The remaining part of the EMC effect at $x \geq 0.5$ is consistent with dominance of the contribution of SRCs. Implications for extraction of the F_{2n}/F_{2p} ratio are discussed. Smallness of the non-nucleonic degrees of freedom in nuclei matches well the recent observation of a two-solar mass neutron star, and while large pn SRCs lead to enhancement of the neutron star cooling rate for kT$\leq$ 0.01 MeV.

1 Introduction

To resolve microscopic structure of nuclei one needs to use high energy high momentum transfer probes. Otherwise the high frequency components of the nuclear wave function enter only as renormalization/cutoff parameters in the descriptions of the low energy phenomena, like for example in chiral effective field theory.

The key questions which can be addressed by using high energy processes and which are relevant for the description of high density cold nuclear matter at the neutron star densities are (i) can nucleon be good quasiparticles for description of high energy processes off nuclei, (ii) does the notion of the momentum distributions in nuclei make sense for $k \geq m_\pi$, (iii) what is probability and structure of the short-range/ high momentum correlations in nuclei, (iv) what are the most important non-nucleonic degrees of freedom in nuclei, and (v) what is the microscopic origin of intermediate and short-range nuclear forces. Below we summarize the recent progress in the studies of hard nuclear processes which allows to address several of these questions.

2 Recent progress in the studies of the SRCs in nuclei

Singular nature of NN interaction at large momenta/ small internucleon distances leads to universal structure of SRC and the prediction of the scaling of the ratios of the cross sections of $x > 1$ scattering at sufficiently large $Q^2 \geq 2\text{GeV}^2$ [1]. In particular for $1 + k_F/m_N < x < 2$:

$$R_A(x, Q^2) = 2\sigma(eA \to e + X)/A\sigma(e^2H \to e + X). \tag{1}$$

Here $a_2(A)$ has the meaning of the relative probability of the two nucleon SRCs per nucleon in a nucleus and in the deuteron. The first evidence for such scaling of the ratios was reported in [2]. The extensive studies were performed using various data taken at SLAC in [3]. The experiments performed at Jlab allowed to explore the scaling of ratios in the same experiment. In [4, 5] the scaling relative to ^{3}He was established. Very recently the results of the extensive study of the nucleus/deuteron ratios were reported in [6] allowing a high precision determination of the relative probability of the two nucleon SRCs in nuclei and the deuteron. The results of [6] are in a good agreement with the early analysis of [3], see Fig. 1.

Several theoretical observations are important for interpretation of the scaling ratios: (a) The invariant energy of the produced system for the interaction off the deuteron is small - $W - m_{^2H} \leq 250$ MeV so production of inelastic final states is strongly suppressed. Correspondingly, scattering off exotic configurations like hidden color configurations which decay into excited baryon states, Δ's, etc is strongly suppressed in the discussed kinematics, (b) The closure is valid for the final state interaction of the nucleons of the SRC and the residual nucleus system. Only the f.s.i. between the nucleons of the SRC contributes to the total (e,e') cross section [3, 8]. Since this interaction is the same for light and heavy nuclei it does not modify the scaling of the ratios, (c) In the limit of large Q^2 the cross section is expressed through the light - cone projection of the nuclear density matrix, $\rho_A^N(\alpha)$ that is the integral over all components of the interacting nucleon four momentum except $\alpha \equiv p_-/(m_A/A)$ where $p_- = p_0 - (\vec{p} \cdot \vec{q})/|\vec{q}|$. The ratio of the cross sections reaches a plateau at $x(Q^2)$ corresponding to the scattering off a nucleon with minimal momentum $\sim k_F$ indicating that the dominance of two nucleon SRC sets in just above the Fermi surface. A further confirmation of dominance of two nucleon correlation comes from the observation [3] of precocious scaling of the ratios plotted as a function of the minimal α for the scattering off two nucleon SRC at rest (the Fermi motion of the pair practically cancels out in such a ratio)[2]: $\alpha_{tn} = 2 - (q_0 - q_3/2m_N)(1 + (\sqrt{W^2 - 4m_N^2}W)$, where $W^2 = 4m_N^2 + 4q_0m_N - Q^2$. The precocious α_{tn} scaling indicates that R_A is equal to the ratio of the light cone density matrices of the deuteron and nucleus. It also strongly indicates that SRCs of baryon charge two are predominantly build of two nucleons rather than some exotic states.

To probe directly the structure of the SRCs it is advantageous to study a decay of SRC after one nucleon of the SRC is removed which is described by the nuclear decay function

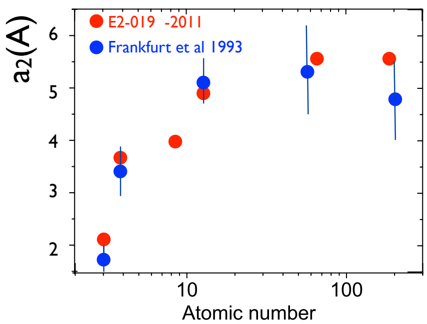

Figure 1: Comparison of the first determination of $a_2(A)$ based on the analysis of the SLAC data [3] with the most recent Jlab measurements [6].

[1, 2]. In the two nucleon SRC approximation the decay function is simply expressed through the density matrix as the removal of one of the nucleons of the correlation results in the release of the second nucleon with probability of one. A series of the experiments was performed at BNL and Jlab which studied (p,2p), (e,e'p) reactions in the kinematics where a fast proton of the nucleus is knocked out, see review and references in [7, 8]. In spite of very different kinematics – removal of forward moving nucleon in the ^{12}(p,2p) case and backward moving proton in the ^{12}C(e,e'p) case, different probes and different momentum transfer $-t \approx 5$ GeV^2 and $Q^2 = 2$ GeV^2 – the same of the neutron emission pattern is observed - the neutron is emitted with a probability $\sim 90\%$ in the direction approximately opposite to the initial proton direction with the correlation setting in very close to $k_F(C) \sim 220$ MeV/c. The Jlab experiment observed in the same kinematics both proton and neutron emission in coincidence with $e'p$ and found the probability of the proton emission to be about 1/9 of the neutron probability. Hence the data confirm the our theoretical expectation that removal of a fast nucleon is practically always associated with the emission of the nucleon in the opposite direction with the SRC contribution providing the dominant component of the nuclear wave function starting close to the Fermi momentum. The large pn/pp ratio also confirms the standard expectation of the nuclear physics that short-range interactions are much stronger in the isospin zero channel than in the isospin one channel. Saturation of the probability provides an independent confirmation of the conclusion that at least up to momenta $\sim 500 \div 600$ MeV/c SRC predominantly consist of two nucleons.

3 New developments in the studies of the EMC effect

The deep inelastic scattering off nuclei can be described in the impulse approximation as the convolution of the LC density matrix and the elementary cross section:

$$F_{2A}(x,Q^2) = \int_0^A \frac{d\alpha}{\alpha}\rho_A^N(\alpha)F_{2N}(\frac{x}{\alpha},Q^2), \tag{2}$$

where $x = AQ^2/2q_0m_A$ and $\rho_A^N(\alpha))$ satisfies the baryon charge conservation sum rule: $\int_0^A \frac{d\alpha}{\alpha}\rho_A^N(\alpha) = A$. If the nucleus in the fast frame consists only of nucleons, $\rho_A^N(\alpha))$ also satisfies the momentum sum rule: $\int_0^A \alpha\frac{d\alpha}{\alpha}\rho_A^N(\alpha) = A$. Together these sum rules imply that in the many nucleon approximation the EMC ratio $R_A(x,Q^2) = F_{2A}(x,Q^2)/F_{2N}(x,Q^2)$ should be slightly below one for a range of x below $x_0 = 2/(1+n)$ where $F_{2N}(x) \propto (1-x)^n$ and exceed one for $x > x_0$. Significant deviation of the EMC ratio from these expectations clearly indicates presence of non-nucleonic degrees of freedom in nuclei.

We have demonstrated recently [9] that two effects should be taken into account before considering modifications of the many nucleon approximation for the nuclear wave function: presence of the Coulomb field in a fast nucleon and the difference between the definition of the Bjorken variable in the theoretical expression (Eq. 1) - $x = AQ^2/2q_0m_A$, and the one used in the experimental papers - $x_p = Q^2/2q_0m_p$.

Atomic nuclei carry electric charge. Therefore the Coulomb field of a nucleus is a fundamental property of the nucleus in its rest frame. Under the Lorentz transformation to the frame where the nucleus has a large momentum, the rest frame nucleus Coulomb field is transformed into the field of equivalent photons. This phenomenon is well known as Fermi - Weizsacker - Williams approximation for the wave function of a rapid projectile with nonzero electric charge. Application of this techique allows to evaluate the role of photon degrees of freedom in the partonic nucleus structure. In particular we find for an additional (to the case of the system of free nucleons) light-cone (LC) fraction of the nucleus momentum carried by photons [9] [1]

$$\lambda_\gamma = \int_0^1 dxxP_\gamma(x,Q^2) = \alpha_{em}\frac{2}{\sqrt{3}\pi}\frac{Z(Z-1)}{A}\frac{1}{m_N R_A}. \tag{3}$$

The leading effect $\propto Z^2$ is due to the coherent emission by the nucleus as a whole, and the term $\propto Z$ is due to the subtraction of the incoherent emission of photons by individual protons. Numerically $\lambda_\gamma(^{12}C) = .11\%; \lambda_\gamma(^{56}Fe) = .35\%; \lambda_\gamma(^{197}Au) = 0.65\%$. Presence of the dynamic photon field modifies the parton momentum sum rule:

$$\int_0^A \left[(1/A)(xV_A(x,Q^2) + xS_A(x,Q^2) + xG_A(x,Q^2))\right]dx = 1 - \lambda_\gamma. \tag{4}$$

[1] This formulae corrects corresponding expression of ref.[9] where numerical coefficient was overestimated by a factor ~ 2.6.

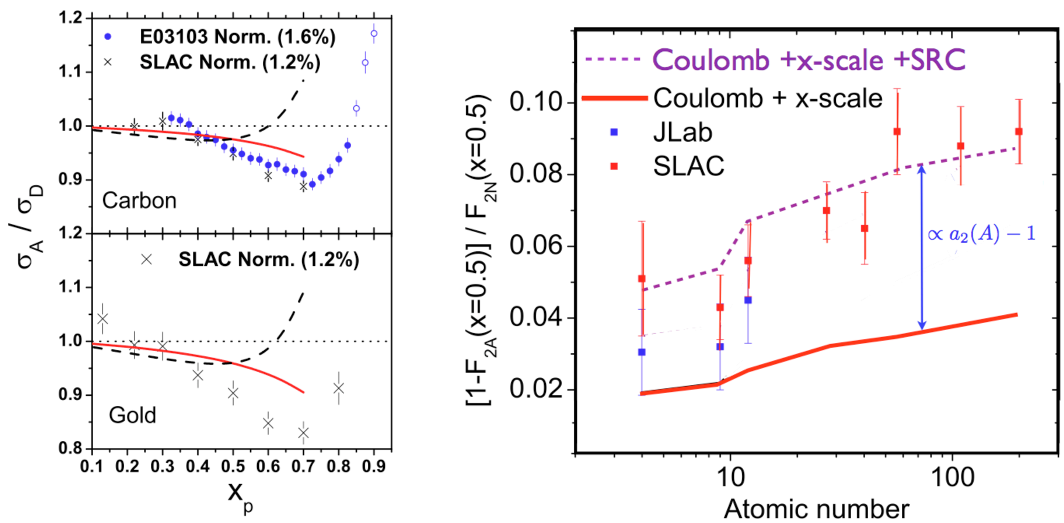

Figure 2: Solid lines are results of calculation taking into account the Coulomb effect and the effect of proper definition of x. In Fig. 2b the dashed line is the contribution of the hadronic EMC effect due to SRCs normalized for large A with the A-dependence given by $a_2(A)$ from [6]. The dashes lines in Fig. 2b are result of adding the effect of the Fermi motion. The data are from the SLAC and Jlab experiments [10, 11].

This effect has to be taken into account in the analyses of the nuclear pdfs. In particular it leads to a $\sim 1.3\%$ reduction of the momentum fraction carried by gluons in heavy nuclei since it is determined using Eq.4 and the F_{2A}/F_{2^2H} data.

The depletion of the LC fraction carried by nucleons leads to a significant EMC effect for $A \geq 50$:

$$R_A(x,Q^2) - 1 = -\lambda_\gamma x F_N'(x,Q^2)/F_N(x,Q^2). \tag{5}$$

Correcting for the difference between x_p used in the experimental papers and x which enters in the convolution expression Eq.2 [1] also leads to a EMC like effect for R_A. It can be taken into account by the substitution $\lambda_\gamma \to \lambda_\gamma + (\epsilon_A - \epsilon_{^2H} - (m_n - m_p)(N-Z)/A)/m_p$ in Eq. 5. The Coulomb field effect is much smaller than the x-rescaling for $A \leq 12$, while for $A \sim 200$ it is as large as the x-rescaling effect. Combined these two effects leads to the solid curves in Fig. 2. One can see that these two *model independent* effects explain $\approx 50\%$ of the EMC effect for $x \leq 0.5$ where Fermi motion effects are small. For $x > 0.5$ where Fermi motion contribution becomes large, an additional effect of modification of the hadronic component of the nucleus wave function is necessary mostly to compensate the Fermi motion effect. The "hadronic EMC effect" is $\approx 4\%$ for $A \geq 50$ for x=0.5 and grows rapidly with further increase of x: $\sim 15\%$ for x=0.6, $\sim 25\%$ for x=0.7. This steep x-dependence is consistent with the expectation of the color screening model that maximal suppression $\sim 20\%$ occurs for very large x where point like configurations dominate in F_{2N}

[12, 13].

It was demonstrated in [12, 13] that a bound nucleon deformation is proportional to the nucleon's kinetic energy (the nucleon off-shellness). Hence the EMC effect is proportional to the average kinetic nucleon energy, which is dominated by the contribution of the SRCs. In Fig. 2b we plot $1 - R_A(x = 0.5)$ since the Fermi motion does not contribute for this x [1]. One can see that the A-dependence of the "extra" EMC effect for F_{2A}/F_{2^2H} is indeed roughly consistent with the measured A-dependence of $a_2(A) - 1$ (the same is true for x=0.6, 0.7).

Our analysis indicates that the non-nucleonic components contribute significantly only in nucleons with $x \geq 0.5$ quarks. Such configurations occurs with a very small probability $\sim 2\%$. Hence we conclude that the probability of exotic component relevant for the large x EMC effect is $\sim 0.2\%$. Since the residual effect for smaller x is $\leq 1 \div 2\%$ we conclude that overall the probability of the exotic component in nuclei is $\leq 2\%$. This is consistent with the results of the analysis described in Sect. 2 that SRCs are dominated by the nucleonic degrees of freedom.

In the case of the scattering off the deuteron the Coulomb and x-rescaling effects are practically negligible and only hadronic effect is present. Since the hadronic EMC effect is proportional to the average nucleon kinetic energy (average virtuality) it is expected to be approximately factor of 4 smaller for the deuteron than for medium and heavy nuclei [12], [13]. As a result the EMC effect for the deuteron $(R_D(x, Q^2) = F_{2D}/F_{2N}(x, Q^2))$ say for $x = 0.5$ is approximately 1/4 of the difference between the dashed and solid curves in Fig. 2b for $A \geq 50$ - that is $1 - R_D(0.5, Q^2) \approx 0.01$ (which is a factor of ~ 2 smaller than if one assumes that all the EMC effect is due to the scattering off the SRCs) leading to a reduction of the extracted F_{2n}/F_{2p} ratio at large x.

4 Some implications for neutron stars

The small probability of the nonnucleonic degrees of freedom in nuclei including SRC which follows from the studies of the hard nuclear phenomena fits well with the recent observation[14] of a heavy neutron star of about two Solar masses - models where nonnucleonic degrees of freedom are easily excited do not allow existence of such heavy neutron stars.

Our focus is on the outer core where nucleon density is close to the nuclear one: $\rho \sim (2 \div 3)\rho_0$, where $\rho_0 \approx 0.16$ nucleon/fm^3 and the ratio of the proton and neutron densities $x \sim 1/10$, corresponding to

$$k_F(p)/k_F(n) = (N_p/N_n)^{1/3} \equiv x^{1/3} \ll 1. \tag{6}$$

Since the probability of the pn SRC grows with the neutron density which is a factor of $4 \div 6$ higher for $\rho \sim (2 \div 3)\rho_0$. As a result the neutron gas "heats" the proton gas leading to practical disappearance of the proton Fermi surface [8].

The high momentum tail of proton, neutron distributions are directly calculable. In the leading order in k_F^2/k^2 the occupation numbers for protons and neutrons with momenta above Fermi surface are

$$f_n(k,T=0) \approx (\rho_n)^2 \left(\left(\frac{V_{nn}(k)}{k^2/m_N}\right)^2 + 2x\left(\frac{V_{pn}(k)}{k^2/m_N}\right)^2\right), \tag{7}$$
$$f_p(k,T=0) \approx (\rho_n)^2 \left(x^2\left(\frac{V_{pp}(k)}{k^2/m_N}\right)^2 + 2x\left(\frac{V_{pn}(k)}{k^2/m_N}\right)^2\right).$$

Since there is an equal number of protons and neutrons above Fermi surface, but $x \ll 1$, the effect is much larger for protons than for neutrons.

As a result, the internucleon interaction tends to equilibrate momenta of protons and neutrons -strong departure from the ideal gas approximation. The Migdal jump in the proton momentum distribution almost disappears in this limit. The suppression of the proton Fermi surface leads to the suppression of the proton superconductivity. At the same time the superfluidity of neutrons and proton-neutron pairs is not excluded.

Another effect is the large enhancement of neutrino cooling of the neutron stars at finite temperatures [8]. The enhancement (factor of R as compared to the URCA process) is due to presence of the proton holes in the proton Fermi sea. For example taking $x = 0.1$, and the neutron density ρ_0, we find for the temperature kT $\ll$ 1 MeV:

$$R \approx 0.1(MeV/kT)^{3/2}, \tag{8}$$

and much larger enhancement for $x \ll 0.1$ where the URCA process is not effective. Since the temperature of the isolated neutron star drop below 0.01 MeV after one year, the discussed mechanism leads to a large enhancement of cooling.

5 Conclusions

The impressive experimental progress of the last few years - discovery of strong short range correlations in nuclei with strong dominance of I=0 SRC - confirmed a series of our predictions of 80's and has proven validity of general strategy of using hard nuclear reactions for probing microscopic nuclear structure. It provides a solid basis for the further studies. Several experiments are under way and several are already a part of the planned 12 GeV Jlab research. The hadronic EMC effect is a factor ~ 2 smaller for $x \leq 0.5$ than was thought previously, but it kicks in rapidly at $x > 0.5$ implying that the tagged structure function studies should observe a transition from nearly free nucleon like F_{2N} for $x \leq 0.45$ to a strongly deformed F_{2N} at $x \sim 0.6$. Nucleons remain practically undeformed up to the local densities comparable to the neutron star densities which is consistent with a stiff equation of state for the neutron stars. A direct observation of 3N SRCs, nonnucleonic degrees of freedom in nuclei (Δ-isobar like configurations, etc) which are of direct relevance

for the neutron stars core dynamics are on the top of the agenda for the future research. Observation of these effects will be one of the aims of our data mining program at Jlab, as well as of a number of experiments at 12 GeV. Complementary experiments with hadron beams (FAIR, J-PARC) are highly desirable.

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